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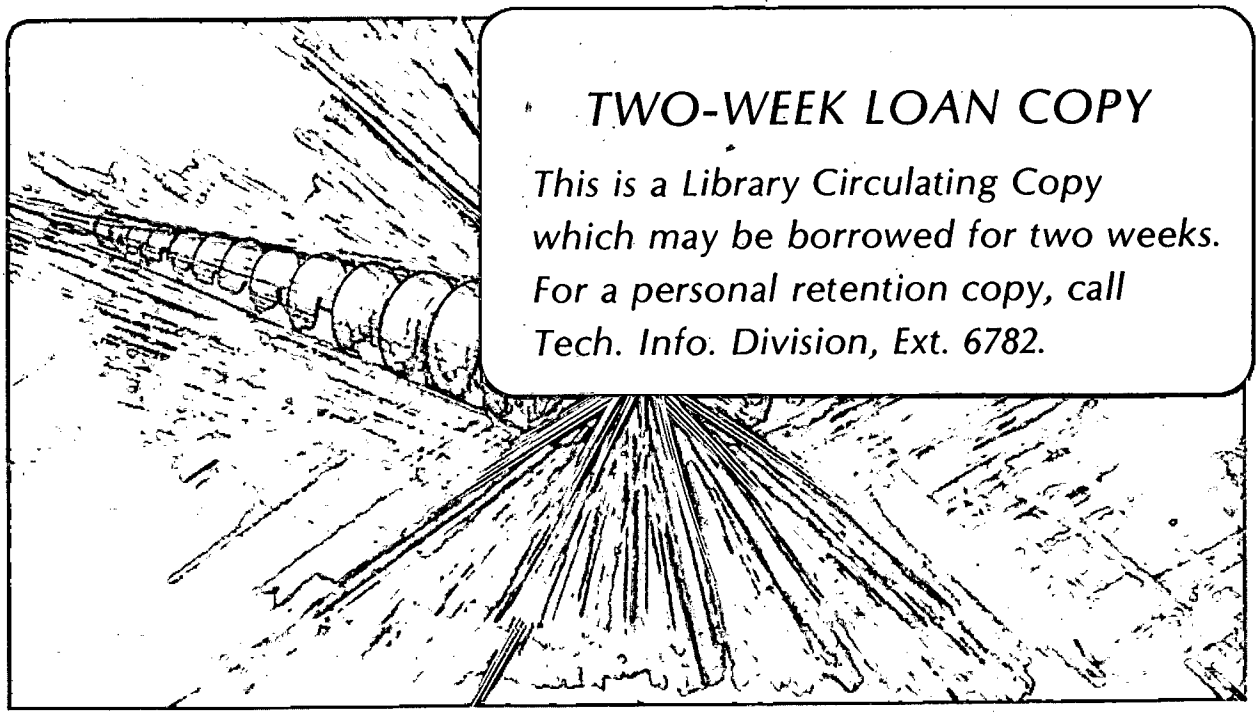

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RADIATIVE ELECTRON CAPTURE BY Cl IONS INCIDENT ON C and Cu FOILS*

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ABSTRACT

Radiative electron capture (REC) cross sections for 40-80 MeV Cl ions incident on thin C foils are reported and compared with previous results using Cu targets. We find that the measured REC cross section per K vacancy scales according to the number of "free" electrons on the target atom, i.e., those bound target electrons with a velocity much less than the incident projectile velocity. Comparison is made with the free-electron theory of Bethe and Salpeter and good agreement is obtained. Experimental and theoretical results are compared with those of Lindskog et al., and consideration is given to different ways of computing the theoretical REC cross section.

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We have previously measured radiative-electron-capture (REC) cross sections for Cl ions in collisions with thin Cu targets.[1] The measured REC yields were properly normalized to the fraction of ions with K vacancies by taking into account target-thickness effects[2,3] thereby giving the REC cross section per K vacancy. The results were in good agreement with predictions based on the free-electron theory of Bethe and Salpeter.[4]

In this comment we report an extension of these measurements for Cl ions incident on thin C targets. Furthermore, we present a modification of the method used to calculate the theoretical cross section from the Bethe-Salpeter theory[4], giving better agreement with the experimental results. The experimental and theoretical results presented here are compared with those of Lindskog et al.[5]

Cl ions with energies 40, 60, and 80 MeV obtained from the Triangle Universities Nuclear Laboratory FN Tandem Van de Graaff accelerator were incident on C foils of thickness 10-150 $\mu g/cm^2$. X rays were detected in air, through a 25.4-μm Mylar window, at 90° to the beam with a Si(Li) detector. Additionally, a 12.7-μm Al absorber was used to attenuate the characteristic x-ray intensity relative to the REC. Normalization of the incident beam intensity was accomplished by detecting scattered projectile ions and recoiling target atoms in a silicon surface barrier detector. Absolute detection efficiency of x rays was determined by methods previously described[1,6].

Analysis of the data was carried out according to the method of Ref. 1. In the present work the incident charge states were 6^+, 8^+, and 10^+ for 40, 60, and 80 MeV, respectively. Hence, the analysis for $q < Z_1 - 2$ $(A = 0)$ of Ref. 1 is applicable in the present case.

The analysis of the 80 MeV data for Cl + C was complicated by the fact that a substantial fraction of the projectile ions develop two K vacancies in passage through the foil, with the ratio of ions having two K vacancies to those with one K vacancy varying from ~8-30% over the range of target thicknesses (10-150 $\mu g/cm^2$) investigated.[7] In the case of the characteristic x rays, the contribution due to two K vacancies is resolved and can be subtracted from the measured K x-ray intensity. For radiative capture, however, the contribution due to projectiles with two K vacancies is not resolved, and so we have no way of determining the fraction of the measured intensity due to such ions. Since the measured REC yield $d\bar{\sigma}_{REC}/d\Omega$ is directly proportional to the cross section per K vacancy $d\sigma^o_{REC}/d\Omega$ (Ref. 1), the net effect will be to overestimate $d\sigma^o_{REC}/d\Omega$ for 80 MeV by at most 30% and, more probably, somewhat less than this.

Values of the differential REC cross section $d\sigma^o_{REC}d\Omega$ at 90° <u>per K vacancy</u> obtained from the present analysis for Cl + C are shown in Fig. 1 along with our previous results for Cl + Cu[1]. Although the beam energy dependence is about the same for the two targets, the measured cross sections in Cu targets are roughly a factor of three higher than those in C targets. This is attributed to the fact that there are more "free" electrons to be captured in Cu than in C.

Experimental cross sections are compared with the free-electron theory of Bethe and Salpeter[4] from which the differential cross sections at 90° were calculated assuming a $\sin^2\theta$ dependence[8-11] for the REC intensity. The dashed curve is the cross section for capture of a single free electron by the incident Cl ions. However, each target atom has several electrons which can be captured radiatively. In a previous

analysis[1] we rather arbitrarily assumed that all of the M and N-shell electrons (19 electrons) in Cu contributed equally to REC, and in a later publication[6], this was modified so that only the eleven outermost electrons in Cu were included in the calculations. The criterion to be used in determining which electrons are to be included in the Bethe-Salpeter calculations is that the captured electron be essentially "free" with respect to the incident projectile. This condition may be expressed by the relation

$$\frac{v_e}{v} = \left(\frac{E_B/m_e}{E/M}\right)^{1/2} \ll 1 \qquad (1)$$

where v_e is the bound electron velocity in the target atom and v is the laboratory incident projectile velocity, E_B the initial electron binding energy, E the incident projectile energy and m_e and M the electron and projectile masses, respectively. If we require that $v_e/v < 0.1$, a simple calculation, using the binding energies listed by Bearden and Burr[12], shows that this condition is satisfied only for the eleven outermost electrons in Cu and the four L electrons in C.

If the single electron Bethe-Salpeter[4] cross section shown in Fig. 1 is multiplied by the factors eleven and four, respectively, for Cu and C, we obtain the solid curves shown in the figure. The results are seen to be in excellent agreement with not only the beam energy dependence but also with the absolute magnitude of the measured cross sections. Any remaining discrepancies are likely attributable to either statistical uncertainties in the measured x-ray yields or to systematic errors in the absolute detection efficiency determination.

The present results can be compared with those of Lindskog[5] et al. for 30, 40, 48, and 58 MeV Cl ions incident on C foils, which are shown by the open squares in Fig. 1. The experimental cross sections reported by these authors have been multiplied by $3/8\pi$ in order to obtain the differential cross section at 90°.[11] It is seen that the agreement with the present measurements is poor. The reason for this discrepancy is not completely known. A likely possibility is that Lindskog et al.[5] normalized the measured REC intensity to the characteristic K x-ray intensity from decays inside the foil following the procedure of Schulé et al.[9] This procedure suffers from the fact that it is difficult to accurately determine the x-ray intensity from decays inside the foil alone and, furthermore, the radiative decay time for the highly ionized projectile must be known. Another cause for the discrepancy may be the difficulty of accurately determining the absolute detector efficiency.

In addition to the disagreement in experimental values between Ref. 5 and the present work, there is also disagreement in the theoretical values calculated from the Bethe-Salpeter theory[4]. It should be pointed out that, in the comparison with experimental results, Lindskog et al. multiplied the theoretical single electron cross section by six rather than four, as we have done, to account for the additional electrons on C.

In order to determine the reason for the discrepancy, let us examine more closely the calculation of theoretical REC cross sections from the expression given by Bethe and Salpeter,[4] namely

$$\sigma_{REC}^{BS} = 9.1 \times 10^{-21}\left(\frac{n^3}{1+n^2}\right)^2 \frac{\exp(-4n \arctan n^{-1})}{1-\exp(-2\pi n)} \ (cm^2) \qquad (2)$$

where $\eta = [E_K/(E_{REC}-E_K)]^{1/2}$ in which E_K is the K-shell binding energy of the electron after capture and E_{REC} is the energy of the emitted photon. For capture of a free electron by a bare projectile, η is just the ratio of the electron velocity after capture to the initial velocity of the captured electron with respect to the ion. In this case, the binding energy may be obtained by hydrogenic scaling and so $\eta = Ze^2/\hbar v$. This latter expression for η is the one used by Lindskog et al. to compute σ_{REC}^{BS}. There are two problems with this method. First, the incident ion is not fully stripped and, hence, the bound electron velocity so obtained may not be accurate. Second, the captured electron is not really free since it is bound in the target material, and hence, has a component of velocity in addition to the relative motion between target and projectile.

In our calculations we have used the expression for η written in terms of E_K and E_{REC}. The advantage of this method is that values for E_K and E_{REC} can be obtained from experiment, thereby giving more accurate values for these quantities. The value of E_{REC} is given directly by experiment and was taken to be the energy corresponding to the centroid of the observed REC peak. Two different ways of determining E_K from experiment were investigated. In the first method, the K-shell binding energy E_K for the highly stripped Cl ions was taken to be equal to the sum of the single K-vacancy binding energy for Cl[12] and the measured increase in the Kβ x-ray energy. Since the Kβ x-ray energy (2816 eV)[13] is very close to that of the K-shell binding energy (2822 eV)[12] for a Cl ion with a single K vacancy, we have assumed the same to be true for a multiply-ionized Cl ion. In the second method, the measured REC energy E_{REC} is used to determine E_K,

since, to a very good approximation, E_{REC} is given by [9,14]

$$E_{REC} = E_K + \frac{m_e}{M} E. \qquad (3)$$

This expression is strictly valid only for the capture of a free electron since it neglects the contribution to E_{REC} due to the initial binding in the target atom. However, so long as only those electrons are considered for which eq. (1) is valid, this contribution will be small. Then, since the value of E_{REC} is given by experiment, eq. (3) may be used to compute E_K.

Figure 2 shows the measured REC energies as a function of beam energy compared with two calculations. In each case E_{REC} was calculated from eq. (3). For the dashed curve E_K was taken to be equal to the hydrogenic K-shell binding energy, $Z_{eff}^2(13.6\ eV)$, where $Z_{eff} = Z-0.3$. For the solid curve E_K was determined, as discussed above, from the shifted $E_{K\beta}$ energy. It is seen that the solid curve is in much better agreement with the measured REC energies, indicating that this latter method of determining E_K gives more realistic values. The increasing deviation between the data and the solid line for increasing beam energy reflects the fact that the Kβ x-ray energy provides a relatively poorer estimate of E_K for the higher incident energies (i.e. as the ionization of the projectile increases).

These results suggest that, using the measured REC energy to calculate E_K from eq. (3) is not only reasonable, but probably provides the best estimate for E_K. Furthermore, contributions to E_{REC} from the initial

binding of the captured electron in the target are implicitly included in the calculation of E_K by this method.

In Table I and Fig. 3 we show the results of using hydrogenic scaling to calculate σ_{REC}^{BS} from eq. (2) compared with the results of using experimentally determined values for E_K and E_{REC} to calculate σ_{REC}^{BS}. It is seen that the theoretical REC cross section may vary by as much as 35-60% depending on which method is used. The calculated σ_{REC}^{BS} obtained using the values of E_K from eq. (3) are believed to be the most accurate since they are derived from values of E_K and E_{REC} which most closely represent the experimental situation. Hence, the values of σ_{REC}^{BS} given by the solid curve in Fig. 3 were multiplied by $3/8\pi$ to give the dashed curve in Fig. 1. These results, combined with the fact that Lindskog et al. multiplied the theoretical Bethe-Salpeter cross section by six rather than four for Cl + C, account for the discrepancy in theoretical calculations between Ref. 5 and the present work.

In conclusion we have shown that when REC cross sections are properly normalized to the fraction of ions with K vacancies, according to the procedure of Ref. 1, excellent agreement is obtained with predictions of the Bethe-Salpeter theory by assuming a $\sin^2\theta$ dependence for the REC intensity and by taking proper account of the number of "free" electrons on each target atom. Experimental measurements of REC resulting from projectiles incident on foil targets are likely to give inaccurate results unless target thickness effects are taken into account. Furthermore, the present results establish quantitatively, for the first time, that the REC cross section depends strongly on the number of "free" electrons in the target atom.

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Table I. Calculated REC cross sections from the free-electron theory of Bethe and Salpeter (Ref. 4) given by eq. (2). Comparison is made between the values obtained using hydrogenic scaling to calculate σ_{REC}^{BS} with those obtained using experimentally determined values of E_K and E_{REC} to calculate σ_{REC}^{BS} (see text).

		$\eta = Ze^2/\hbar v$		$\eta = [E_K/(E_{REC} - E_K)]^{1/2}$			
E (MeV)	v (10^9cm/sec)	η	σ_{REC}^{BS} (b)	η^a	σ_{REC}^{BS} (b)	η^b	σ_{REC}^{BS} (b)
20	1.05	3.47	1900	2.98	1380	3.15	1550
40	1.49	2.44	892	2.13	658	2.27	760
60	1.82	2.00	571	1.69	383	1.89	501
80	2.10	1.73	407	1.43	257	1.66	369

a) $E_K = E_K^o + \Delta E_{K\beta}$; E_K^o is the K-shell binding energy from Ref. 12 and $\Delta E_{K\beta}$ is the experimentally measured shift in the Kβ x-ray energy.

b) $E_K = E_{REC} - \frac{m_e}{M}E$; m_e and M are the electron and projectile masses, respectively, and E is the incident beam energy.

Figure Captions

Fig. 1. Cl REC differential cross sections at 90° per K vacancy as a function of the incident Cl ion energy. Solid squares: Cl + C, present work; solid circles: Cl + Cu, Ref. 1; open squares: Cl + C, Ref. 5. The dashed curve was calculated from the free-electron theory of Bethe and Salpeter (Ref. 4), assuming a $\sin^2\theta$ angular distribution for REC (Refs. 8-11). The solid curves were obtained by multiplying the dashed curve by factors of four and eleven for C and Cu, respectively, representing the number of "free" electrons on these target atoms (see text).

Fig. 2. Centroid energy E_{REC} of the observed REC peak vs. incident beam energy E. The experimental errors are about the size of the points. Calculated values of E_{REC} were obtained from eq. (3). For the dashed curve, hydrogenic scaling was used to calculate the K-shell binding energy E_K for a highly stripped Cl ion, whereas, for the solid curve, E_K was determined from the measured shift $\Delta E_{K\beta}$ in the Kβ x-ray energy.

Fig. 3. Comparison of the three different methods of computing the theoretical REC cross sections as presented in Table I. All calculations are based on the Bethe-Salpeter theory given by eq. (2). The solid curve was used to obtain the dahsed curve in Fig. 1.

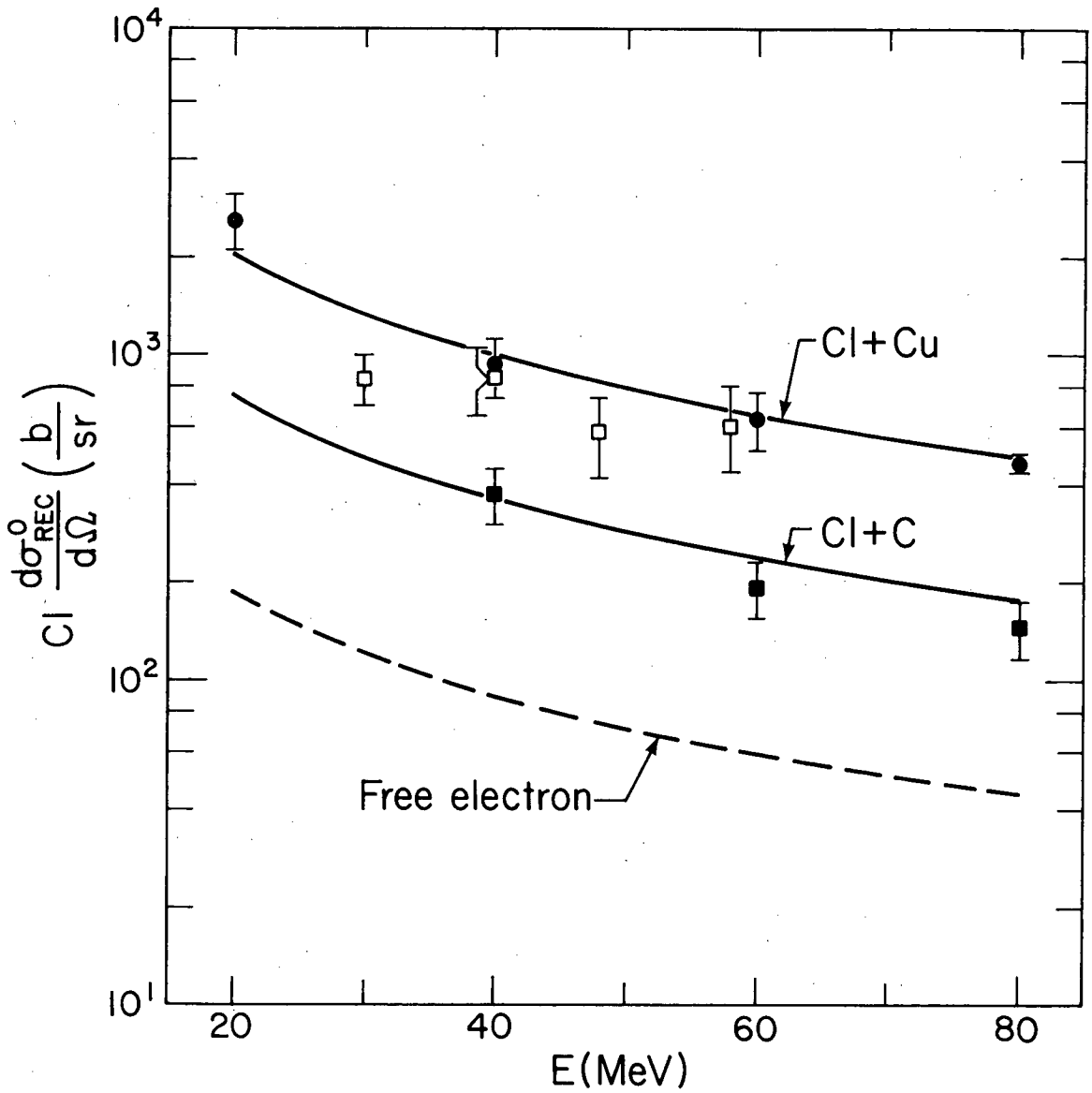
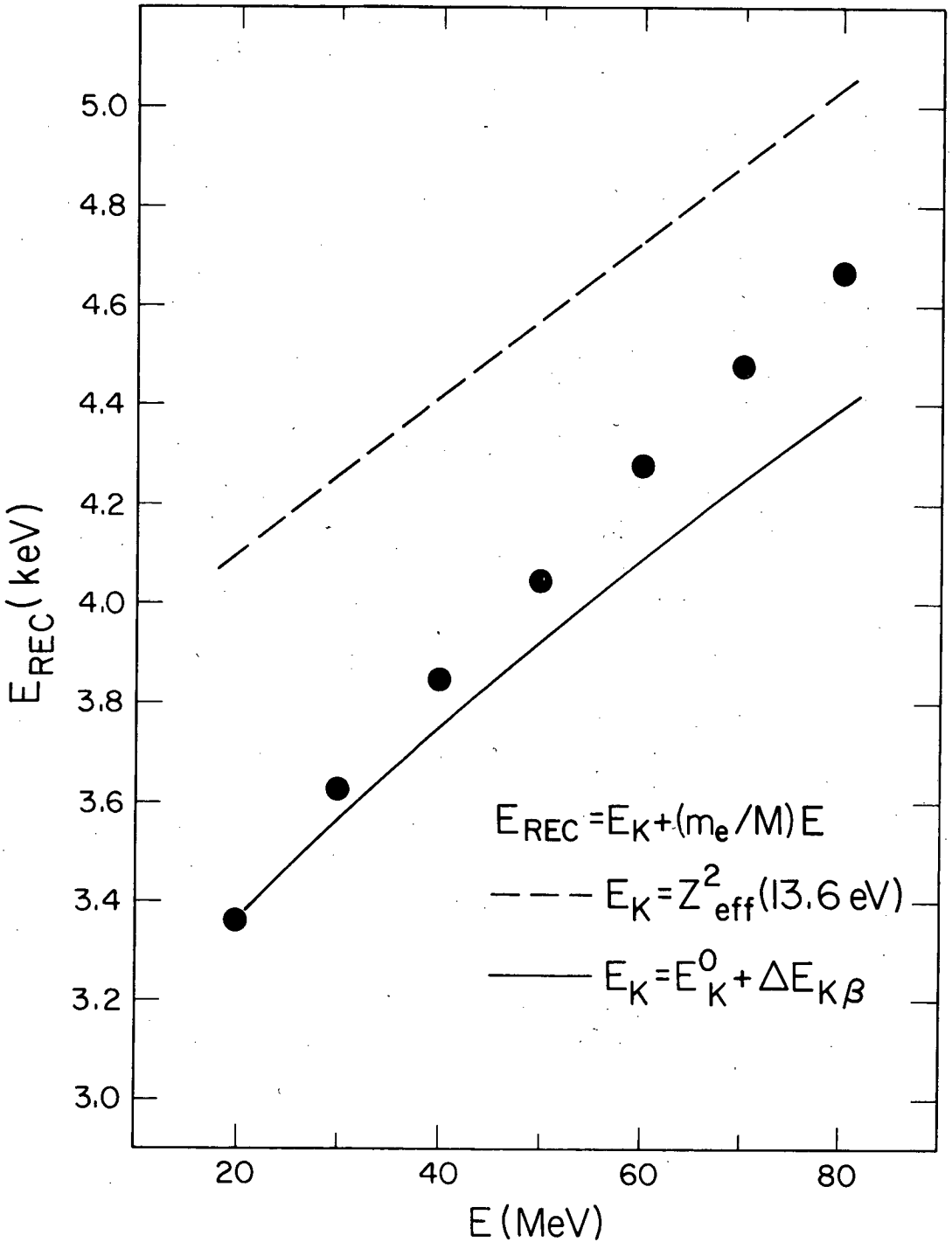

10^4
10^3
10^2
10^1
$Cl \frac{d\sigma^o_{REC}}{d\Omega} \left(\frac{b}{sr}\right)$
Cl+Cu
Cl+C
Free electron
20
40
60
80
E(MeV)
XBL 802-352

Fig. 1



XBL 7911-5086

Fig. 2

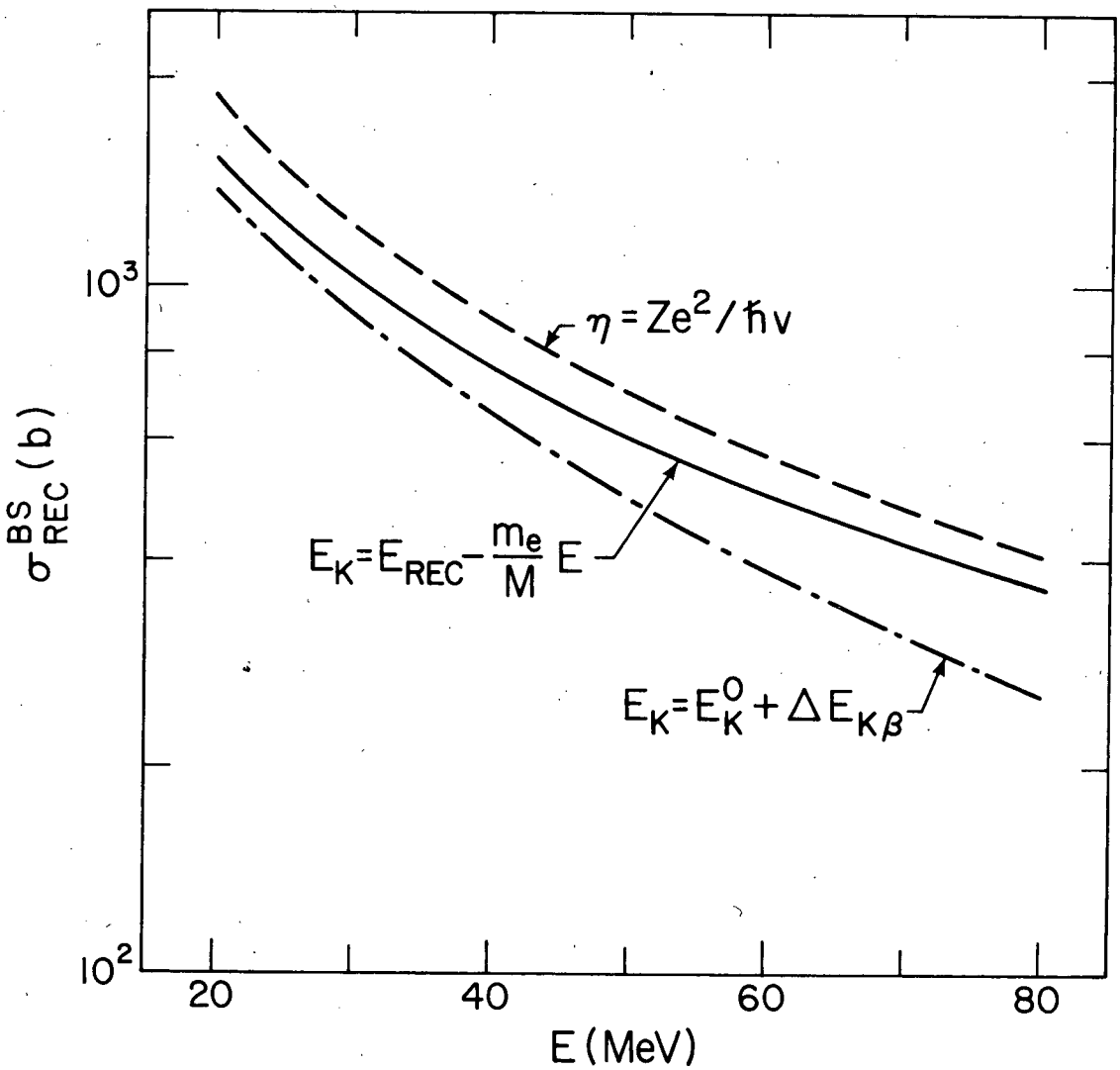

σ^{BS}_{REC} (b)
10^3
10^2
$\eta = Ze^2/\hbar v$
$E_K = E_{REC} - \frac{m_e}{M} E$
$E_K = E^0_K + \Delta E_{K\beta}$
20
40
60
80
E (MeV)
XBL 802-353

Fig. 3

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